

## COSMIC ACCELERATION VERSUS AXION-PHOTON MIXING

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## ABSTRACT

Axion-photon mixing has been proposed as an alternative to acceleration as the explanation for supernovae dimming. We point out that the loss of photons due to this mixing will induce a strong asymmetry between the luminosity,  $d_L(z)$ , and angular diameter distance,  $d_A(z)$ , since the latter is unaffected by mixing. In a first search for such an asymmetry, we introduce a dimensionless mixing amplitude  $\lambda$  such that  $\lambda = 0$  if no photons are lost and  $\lambda \approx 1$  if axion-photon mixing occurs. The best fit to Type Ia supernovae and radio galaxy data is  $\lambda = -0.3^{+0.6}_{-0.4}$  (95% confidence level), corresponding to an unphysical, negative mixing length. This same argument limits the attenuation of light from supernovae due to dust. We show that future  $d_L$  and  $d_A$  data from the Supernova/Acceleration Probe and galaxy surveys such as DEEP2 and KAOS will detect or rule out mixing at more than  $5\sigma$  almost independently of the dark energy dynamics. Finally, we discuss the constraints from the near-maximal polarization of the gamma-ray burst (GRB) GRB 021206. Since mixing reduces the polarization of distant sources, future observations of high-redshift GRBs will provide orthogonal constraints on axion-photon mixing and related scenarios.

*Subject headings:* cosmological parameters — cosmology: theory — elementary particles

*On-line material:* color figures

## 1. INTRODUCTION

The reciprocity relation is a wonderfully powerful result valid for any metric theory of gravity in which photons travel on null geodesics, as long as the photon number is conserved (Etherington 1933; Ellis 1971). It ensures that the luminosity distance,  $d_L(z)$ , is exactly the same as the angular diameter distance,  $d_A(z)$ , up to a factor of  $(1+z)^2$ . In this paper we turn the reciprocity relation around and use it to probe alternatives to cosmic acceleration.

The accumulating evidence for recent cosmic acceleration (Barris et al. 2004; Knop et al. 2003) leaves us with the familiar coincidence problem: why do we live at such a special time? An attractive alternative is that the acceleration is a mirage and not a real feature of the dynamics of our universe.

Although such a nonaccelerating cosmology can be made reasonably compatible with cosmic microwave background (CMB) and large-scale structure (LSS) data (Blanchard et al. 2003), the dilemma then is to explain the dimming of distant Type Ia supernovae (SNIa) and the observed  $\sim 3\sigma$  correlation between the CMB and LSS without acceleration (Boughn & Crittenden 2004; Nolita et al. 2003; Scranton et al. 2003; Fosalba et al. 2003). The latter can perhaps be explained by negative spatial curvature, while the dimming of supernovae can be explained by axion-photon mixing (Csáki et al. 2002a), meaning that the evidence for acceleration is not yet overwhelming.

The basic idea of axion-photon mixing is simple. On average, and on large scales relative to the mixing length,  $1/3$  of photons in the visible would be lost through conversion to a light axion state,  $a$ , in the presence of the cosmic magnetic field  $\mathbf{B}$ . This proceeds through the axion interaction term

$(a/4M)\mathbf{E}\cdot\mathbf{B}$ . Csáki et al. (2002a) argue that an axion mass scale of  $M \simeq 4 \times 10^{11}$  GeV would provide a good fit to SNIa luminosity data as a function of redshift (quantified in Erlich & Grojean 2002) without the need for cosmic acceleration, while still being (marginally) consistent with other constraints (see Deffayet et al. 2002; Mörtzell et al. 2002; Christensson & Fairbairn 2003; Mörtzell & Goobar 2003), especially if nonflat Friedmann-Lemaître-Robertson-Walker (FLRW) models are considered.

Intriguingly, axion-photon (AP) mixing with a similar mass scale can explain the existence of super-GZK (Greisen-Zatsepin-Kuzmin) cosmic rays (Csáki et al. 2003) if the primaries are taken to be photons, since they can travel most of the way as axions and then oscillate back into photons before reaching earth. Axion-photon mixing can therefore provide a simultaneous solution to the super-GZK and coincidence problems and is thus worth further detailed study.

We make four points about the axion-photon mixing scenario:

1. Axion-photon mixing should induce a violation of the reciprocity relation and a fundamental disagreement between the dimensionless coordinate distance,  $y(z)$ , which is inferred from the luminosity,  $d_L(z)$ , and angular diameter distances,  $d_A(z)$ .

2. The observed  $d_A(z)$  should correspond to a decelerating universe if axion-photon mixing is the source of supernovae dimming. However, current estimates of  $d_A(z)$  favor an accelerating universe.

3. Future data from the *Supernova/Acceleration Probe* (SNAP) and KAOS will allow for constraints beyond the  $5\sigma$  level. Tests of number counts from the ongoing DEEP2 survey will provide further tight constraints.

4. Mixing leads to depletion of the polarization levels of extragalactic sources (Csáki et al. 2002a; Mörtzell & Goobar 2003). The near-maximal polarization seen in the gamma-ray burster (GRB) GRB 021206 (Coburn & Boggs 2003) suggests that GRBs may provide powerful constraints on the mixing scenario when more data are available.

In this paper we assume a flat FLRW model consisting of dust ( $\Omega_M$ ) and dark energy  $X$  ( $\Omega_X = 1 - \Omega_M$ ) with a constant equation of state  $w = p_X/\rho_X$ .

## 2. THE RECIPROCITY RELATION

One can define several distances in cosmology. The luminosity distance,  $d_L(z)$ , estimates distances by comparing the absolute luminosity of an object to its observed/apparent luminosity. The angular diameter distance,  $d_A(z)$ , estimates distances based on how the apparent linear size of an object changes with redshift. In metric theories where photons travel on null geodesics and their number is conserved, one can show that these two distances are fundamentally related by the reciprocity relation (Schneider et al. 1992):

$$d_L(z) = (1+z)^2 d_A(z). \quad (1)$$

When the reciprocity relation holds, the dimensionless coordinate distance  $y(z)$  can be estimated from either  $d_L(z)$  or  $d_A(z)$  via the relations  $y(z) = H_0 d_L/(1+z) = H_0 d_A(1+z)$ , where  $H_0$  is the current value of the Hubble constant.

In stark contrast, the reciprocity relation is not obeyed in the axion-photon mixing scenario, nor indeed in any scenario (such as light attenuation due to dust) that effectively violates photon number conservation. As a result,  $y(z)$  estimated from  $d_L$  and  $d_A$  data should disagree, since  $d_A(z)$  is unaffected but the luminosity distance is modified as  $d_L \rightarrow d_L/(P_{\gamma \rightarrow \gamma})^{1/2}$ , where  $P_{\gamma \rightarrow \gamma}$  is the probability that a photon will reach the Earth in a photon state and hence be detected. We use the rather good approximation

$$P_{\gamma \rightarrow \gamma} = \frac{2}{3} + \frac{1}{3} e^{-l/l_{\text{dec}}}, \quad (2)$$

where  $l$  is the proper distance of the supernovae. For SNIa at cosmological distances, the mixing saturates at  $2/3$  (Csáki et al. 2002b), and hence supernovae should appear  $(3/2)^{1/2}$  times further away than they really are, in good agreement with the  $d_L(z)$  predicted by the standard best-fit  $\Lambda$ CDM model with  $\Omega_\Lambda \simeq 0.7$  and  $\Omega_M \simeq 0.3$ . The precise value of the decay length  $l_{\text{dec}}$  depends on the mixing and the galactic magnetic fields. The preferred value of Csáki et al. (2002a) is  $l_{\text{dec}} \approx 1/(2H_0)$ . This motivates the use of a dimensionless suppression amplitude

$$\lambda \equiv (2H_0 l_{\text{dec}})^{-1}, \quad (3)$$

which is 0 if no mixing occurs and 1 in the case of mixing over cosmological distances.

## 3. CONSTRAINTS FROM CURRENT DATA

If axion-photon mixing is to solve the coincidence problem, then we should expect the  $d_A(z)$  data to fit best to a non-accelerating universe. This is not the case, however. There are (at least) three independent data sets for  $d_A(z)$  that give large

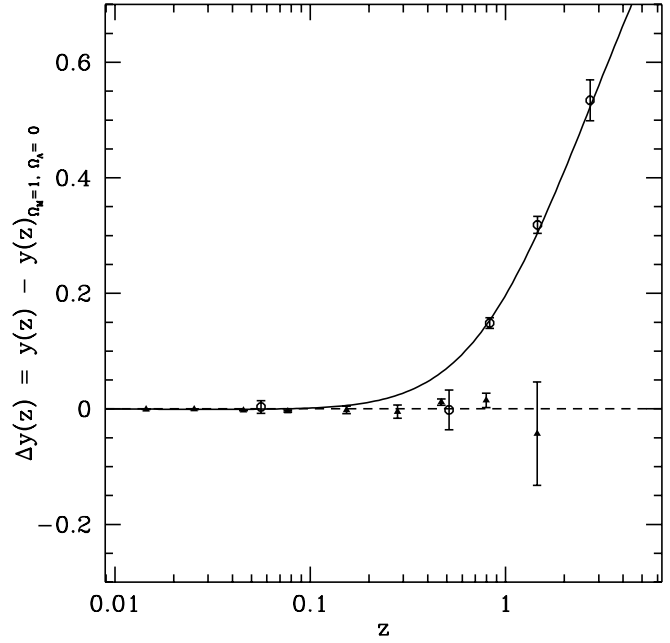


FIG. 1.—Residual value  $\Delta y(z)$  in the dimensionless coordinate distance relative to an  $(\Omega_M, \Omega_\Lambda) = (1, 0)$  universe for redshift-binned SNIa data [ $d_L(z)$ , triangles] “corrected” for the loss of photons predicted by axion-photon mixing and redshift-binned radio galaxy data [ $d_A(z)$ , circles]. The solid curve is  $\Delta y(z)$  for an  $\Omega_M = 0.22$ ,  $\Omega_\Lambda = 0.78$  universe. If mixing were the origin of supernovae dimming, we should expect the radio galaxy data to coincide with the best-fit  $y(z)$  curve of this corrected SNIa data, near  $\Delta y(z) = 0$ ; however, the radio galaxy data lies systematically above this curve, favoring an accelerating universe.

best-fit values of  $\Omega_\Lambda$ , consistent with standard  $d_L(z)$  best fits and an accelerating universe.

Daly & Guerra (2002) and Daly & Djorgovski (2003) analyzed data for 20 bright Fanaroff-Riley type IIb radio galaxies at redshifts between 0.43 and 1.79 and, assuming a flat universe, found  $\Omega_M < 0.5$  and  $-2.5 < w < -0.25$  at the 90% confidence level, where  $w$  is the equation of state of the dominant, nondust component. Another analysis (Jackson 2003) of ultracompact radio sources (Gurvitis 1994; Lima & Alcaniz 2002) at  $z > 0.5$  found that the best-fit flat  $\Lambda$ CDM model has  $\Omega_M = 0.24^{+0.09}_{-0.07}$ .

Searches for comoving standard rulers via peaks in the two-point correlation function of quasars have also been undertaken. Roukema et al. (2002), using a subset of the 2dF QSO Redshift (2QZ) survey, estimated  $\Omega_\Lambda = 0.65 \pm 0.35$ . Assuming a flat universe, they constrain the equation of state of the nondust matter to  $w < -0.35$  at  $2\sigma$ . This approach has been extended recently by Outram et al. (2004) using the full 2QZ survey, allowing for even stronger results. Assuming a flat FLRW model, they find  $\Omega_\Lambda = 0.71^{+0.09}_{-0.17}$  and exclude an  $\Omega_\Lambda = 0$  universe at over 95% confidence.

In summary, all current estimates of  $d_A(z)$  favor an accelerating universe, and since they are unaffected by axion-photon mixing, disfavor it as the explanation for the majority of SNIa dimming. This point is made visually in Figure 1, which shows the binned values of the dimensionless coordinate distance,  $y(z)$ , of the data sets used in our analysis. The SNIa data have been corrected for mixing, and indeed cluster around the nonaccelerating Einstein-de Sitter (EdS) model  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ . We used the combined data sets of Tonry et al. (2003) and Barris et al. (2004), to which we added the new supernovae from Knop et al. (2003). However, the radio

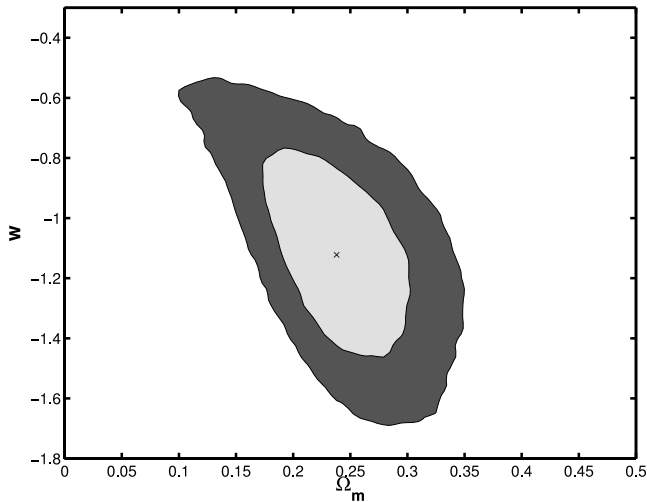


FIG. 2.—Two-dimensional likelihood plot for the equation of state  $w$  and  $\Omega_M$  for the combined SNIa and radio galaxy data sets, with 1 and 2  $\sigma$  contours shown. A flat FLRW universe was assumed. The combined data clearly favor an accelerating low-density universe. [See the electronic edition of the Journal for a color version of this figure.]

galaxy data clearly prefer an accelerating model. These data are a combination of Daly & Djorgovski (2003), Jackson (2003), and Gurvitis (1994). A more detailed description of the data sets can be found in Bassett & Kunz (2003).

In Figure 2 and Figure 3 we show the two-dimensional likelihood plots for  $\Omega_M$ ,  $w$ , and  $\lambda$  for the combined data sets, assuming a flat universe. The overall best fit with axion-photon mixing is  $\Omega_M = 0.24$ ,  $w = -1.1$ , and  $\lambda = -0.3$ . The one-dimensional (marginalized) 95% confidence limits on the parameters are  $0.15 < \Omega_M < 0.33$ ,  $-1.6 < w < -0.6$ , and  $-0.7 < \lambda < 0.3$  (see Fig. 4). The values preferred by axion-photon mixing ( $w = -1/3$  and  $\lambda \approx 1$ ) are ruled out at well over 3  $\sigma$ .

Negative values of  $\lambda$  correspond to the appearance of photons instead of their absorption. This is not impossible in the axion-photon scenario; e.g., if SNIa produce large numbers of axions that become photons on the way to the Earth. Still, it can be argued that this region of the parameter space is unphysical and should be excluded. In this case the 95% upper limit (one-sided) on  $\lambda$  is 0.6, and  $\lambda = 1$  lies at 3  $\sigma$ . This is no longer sufficient to reliably rule out axion-photon mixing. However, the limits on the equation of state remain rather strong with a 95% confidence interval of  $-1.1 < w < -0.5$ , and  $w = -1/3$  remains ruled out at over 3  $\sigma$ . This still renders the scenario unattractive, as the mixing does not alleviate the coincidence problem associated with cosmic acceleration.

#### 4. CONSTRAINTS FROM FUTURE DATA

Future estimates of  $d_L(z)$  from the *SNAP* satellite<sup>1</sup> and  $d_A(z)$  from number counts from the DEEP2 survey and from baryon oscillations from the KAOS survey<sup>2</sup> will allow estimates of  $y_L(z)$  and  $y_A(z)$  at the level of a few percent (Aldering et al. 2002; Linder 2003; Seo & Eisenstein 2003). To investigate the power of future experiments, we used the errors given in the dark energy science case of the KAOS Purple Book (Dey & Boyle 2003) for both the KAOS and *SNAP* experiments. The central values of the data are chosen to match a model with

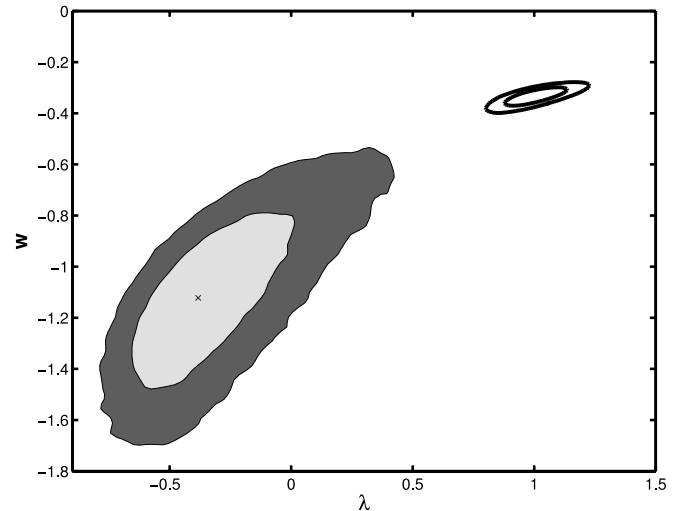


FIG. 3.—Plot of  $\lambda$ - $w$  likelihood for current SNIa and radio galaxy data that peaks at  $(\lambda, w) = (-0.3, -1.1)$ , favoring no mixing ( $\lambda = 0$ ) and acceleration. Axion-photon mixing corresponds to  $\lambda \approx 1$ . The likelihood contours for future data, based on a fiducial nonaccelerating model with mixing,  $(\lambda, w) = (1, -1/3)$ , are also shown at the top right. [See the electronic edition of the Journal for a color version of this figure.]

mixing with an underlying flat FLRW cosmology with  $\Omega_M = 0.3$  and  $w = -1/3$ , which corresponds to the best fit of Csáki et al. (2002b).

Assuming the auxiliary cosmic parameters (e.g.,  $\Omega_M$ ) are well known from other methods by then, we halved the current best estimates and assumed  $\Omega_M = 0.3 \pm 0.02$  as a prior. Although this is not required (and indeed our analysis with current data does not make this assumption), it helps to reduce the error on  $w$  significantly, and it certainly is sensible.<sup>3</sup> With these assumptions, we conclude that we will be able to detect or rule out the mixing scenario at over 5  $\sigma$  after marginalizing over  $w$ . The estimated error bar on  $\lambda$  is less than 0.1 (and is degraded to about 0.13 if no constraints on  $\Omega_M$  are added). The two-dimensional likelihood in the  $\lambda$ - $w$  plane is shown in the upper right hand corner of Figure 3.

<sup>3</sup> When comparing our errors on the equation of state with those of the KAOS Purple Book, one should note that they fit simultaneously several more parameters and that our fiducial model has a higher value of  $w = -1/3$ , which helps to reduce the errors further. A model with  $w = -1$  would have larger errors in  $w$ .

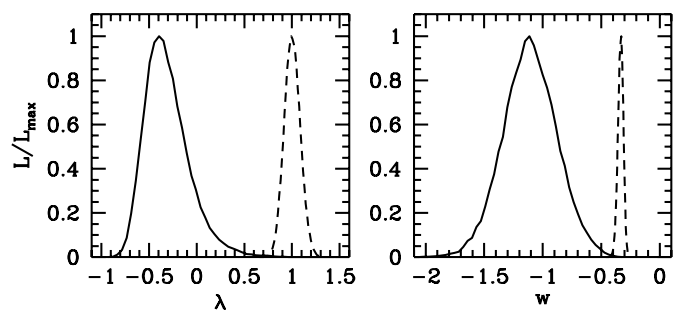


FIG. 4.—One-dimensional likelihood plots for  $\lambda$  and  $w$  for current data (solid line) and hypothetical future data (dashed curve). The value  $\lambda = 0$  corresponds to no photon loss, and  $\lambda = 1$  corresponds to axion-photon mixing. Current data give  $\lambda = -0.3 \pm 0.25$  (1  $\sigma$ ). The fiducial model for the future data is flat with  $(\lambda, w) = (1, -1/3)$  and  $\Omega_M = 0.3$ .

<sup>1</sup> See <http://snap.lbl.gov>.

<sup>2</sup> See <http://www.noao.edu/kaos/>.

Although we have assumed a constant  $w$  here, the beauty of having both  $d_L$  and  $d_A$  information is that it allows us to separate the issue of mixing from the dynamics of the dark energy. At each redshift, axion-photon mixing should lead to fundamentally inconsistent values for  $y(z)$  derived from  $d_L$  and  $d_A$ , respectively.

An estimate of cosmic parameters unbiased by mixing will be available from the Sloan Digital Sky Survey (Matsubara & Szalay 2002), while a further test of mixing is provided by number counts versus redshift,  $dN/dz$ , which depends on  $d_A(z)$ . Since the volume of space as a function of redshift is very sensitive to  $\Lambda$ , number counts is a good test of acceleration. Generally, the number of objects in the range of affine parameter values  $[y, y + \Delta y]$  is (e.g., Ellis 1971; Ribeiro & Stoeger 2003)

$$dN = d_A^2(1+z)n(y)dyd\Omega, \quad (4)$$

where  $n(y)$  is the number density of objects and  $d\Omega$  is the differential solid angle at the observer. Axion-photon mixing alters galaxy number counts by reducing the apparent luminosity of objects at high redshift, at least in the visible range. Since high-redshift objects appear dimmer, the selection function  $\psi$  is altered and faint galaxies will be lost. Therefore, there should be a deficit of objects relative to the case of no axion-photon mixing.

If we therefore compare a standard  $\Lambda$ CDM model against a nonaccelerating model with axion-photon mixing, the difference in number counts at  $z > 1$  is significant. One can consider variants of this basic idea such as the  $dV/dz d\Omega$  test, which, applied to the DEEP2 galaxy survey of  $\sim 50,000$  galaxies with redshifts  $0.7 < z < 1.4$ , should allow an estimate of  $w$  today (unbiased by axion-photon mixing) to  $\sim 10\%$  (Newman & Davis 2000).

However, the mixing mechanism may be constrained in yet another manner. Observations of the polarization of light from GRB 021206 (Coburn & Boggs 2003) have found linear polarization levels of  $\Pi = 0.80 \pm 0.2$  centered very near the maximum allowed by Compton scattering that strongly support synchrotron radiation as the source of at least some GRBs. If GRB 021206 is at a redshift  $z > 0.1$  and Compton scattering is the source of the linear polarization, then the

near-maximal value of  $\Pi$  observed on the Earth leaves little room for depletion due to mixing. However, as pointed out in Csáki et al. (2002a), mixing is intrinsically inhomogeneous. It is possible to have certain lines of sight that experience essentially no mixing at all, depending on the magnetic field traversed. Hence, unless there is a high- $z$  SNIa in the same narrow field of view as the GRB, a single event alone cannot rule out the mixing scenario. Further, the linear polarization of the GRB may not be due to Compton scattering (Lazzati et al. 2004), in which case there might still be room for axion-photon mixing.

## 5. CONCLUSIONS

The dimming of distant Type Ia supernovae (SNIa) remains the most direct evidence for cosmic acceleration. Nevertheless, alternative explanations exist, such as axion-photon mixing, in which roughly one-third of all photons from distant SNIa are lost into axion states. We have pointed out that such mixing will not affect the angular diameter distance  $d_A(z)$  and hence will cause a fundamental asymmetry between measurements of the luminosity distance,  $d_L(z)$ , and  $d_A(z)$  that can be searched for.

In a first search for such asymmetry, we have undertaken a joint analysis of high-redshift SNIa [ $d_L(z)$ ] and radio galaxy data [ $d_A(z)$ ]. The results do not favor the loss of photons and hence disfavor mixing. Future data will improve the limits and be able to test very generally for an asymmetry between  $d_A(z)$  and  $d_L(z)$ . Number counts versus redshift are a promising test, while estimates of  $d_L(z)$  from *SNAP* and  $d_A(z)$  from a large second-generation galaxy survey such as KAOS will allow axion-photon mixing to be detected or ruled out at more than  $5\sigma$ , almost independently of the dynamics of the dark energy, showing the power in constraining nonstandard physics implicit in combining  $d_L(z)$  and  $d_A(z)$  data.

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